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Abstract
When supercooled water droplets hit a rotating wind turbine blade, ice builds up at the leading edge. This heavily influences the aerodynamics of the blade - especially in stall. In severe cases the mass of ice can become a problem, but this is not typical for the few yearly cases of icing in Denmark, as the measured one presented here.

Loads were measured on the 1MW Elkraft test turbine in Denmark at two incidents of icing, namely at 10 m/s and 15 m/s. The loads are compared with measurements from ice-free conditions. The turbine is stall controlled and has a three bladed upwind rotor. It is equipped with standard LM 24 m blades and has a rotor diameter of 50 meters and a rated power of 1MW.

The two most important conclusions of the investigation are that icing reduced mean power by 25%, and that only marginal ice-induced increases of loads were found. Standard deviation of power was actually reduced to half its value, whereas the equivalent ranges of all other reported loads were marginally changed during icing. Activity of the flapwise as well as the edgewise blade bending moment was increased by a factor of two at the blade eigenfrequencies. 1P-activity of the flapwise blade bending moment was increased by a factor of three - probably due to aerodynamic unbalance.

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Contents

1. Introduction

Icing occurs when super-cooled water droplets hit a structure. For wind turbines the problem is more severe than for buildings, because the leading edges of the turbine blades during operation in a super-cooled cloud hit many more droplets. Supercooled clouds only exist at temperatures below zero degree Celsius.

Icing of wind turbine blades happens, when super-cooled droplets hit the leading edge around the point of stagnation. Thus most ice will be found around point of stagnation. At temperatures close to zero degrees not all the super-cooled water in the droplets freeze at first contact with the blade, simply because the energy release at freezing is too big. Some of the water will afterwards freeze, when water is sliding along the profile surface. This in some cases creates air-mixed rough-surfaced ice on the leading edge on both sides of the point of stagnation. It may also create ice-clods on the otherwise smooth surface of the pressureside or suctionside of the profile and thus change the aerodynamics of the profile.

In Denmark icing of wind turbine rotors do not occur often, and has not been much investigated. On the other hand most turbine operaters know that during winter icing of anemometers and wind vanes happen a few times every year, and that at the same time some ice is often found on the blades. It is generally believed that icing of anemometers and wind vanes is a problem because of lost production during malfunction of the instruments, but that it is a small problem. Ice on the blades is considered to be of importance for the safety of people passing below the turbine, when the ice is melting, but neither for production nor loads.

In this report an example of loads measured in Denmark during icing of a rotor is reported. The icing is severe for Denmark, but not in an international perspective. In Ref. 3 the results are compared with measured data from a severe case of icing in Finland and in Ref. 2 measured Cl and Cd data for iced profiles are presented.

2. Turbine Description

The reported measurements come from the Elkraft 1MW wind turbine. It is a test turbine, which can run at different configurations, and some data for the relevant stall controlled configuration is found in Figure 4.1-1 and Figure 4.1-2.

No. Of blades	3
Rotor Diameter	50 m
Hub Height	55 m
Rotor Speed	23.13 RPM
Power Control	Stall
Rotor Tilt	3.5 deg.
Rotor Coning	0.0 deg.
Tip Angle	0.5 deg.
Rotor Weight	23600 kg.
Blade Type	LM24m
Blade Weight	3645 kg
Generator Power	2 x 500 kW
Tower Type	Tapered Tubular
Tower Weight	95000 kg.
Tower Diameter Top/Bottom	3.5m/5.5m
Nacelle Weight	91168 kg.

Figure 4.1-1 Technical data for the Elkraft 1MW wind turbine. Selected from Ref.2.

Vibrational mode	Measured natural frequency (Hz)
First Tower Bending	0.66
First Shaft Torsion	0.88
First Asym.Rotor/Tower Torsion (Yaw)	1.19
First Asym.Rotor/2.TowerBending(Tilt)	1.25
First Sym.Rotor Flapwise/Tower Bending	1.45
First Asym.Rotor Edgewise	2.44
Tower Torsion/Asym. Rotor Flapwise (2nd Yaw)	4.05
2nd Tower Bending/Asym.Rotor Flapwise (2nd Tilt)	3.50
First Flapwise Bladebending (Blade in teststand)	1.45
Second Flapwise Bladebending (B. in teststand)	4.58
First Edgewise Bladebending (Blade in teststand)	2.65

Figure 4.1-2 Measured eigenfrequencies from Ref.2.

3. Measured Electrical Power Output

Figure 4.1-3 shows selected 10-minute averages of electrical power output from the turbine measured the 15th, 16th and 17th of February 1996. During a 5 hour period icing of the rotor occurred and the power output was reduced - the corresponding averages can easily be distinguished in Figure 4.1-3. The reduction in power output can be seen to be of the order of 25% in the concerned wind speed range of 13 to 16 m/s. The period of icing occurred on the 15th from 16.30 to 21.30, and the wind direction was from south west over the sea. Temperatures varied from slightly below to slightly above 0 degrees during this period.

Figure 4.1-4 shows standard deviation of electrical power output measured during the same period as the data in Figure 4.1-3. Obviously the standard deviation of electrical power is lower during icing. The reduction is roughly as much as a factor of two. This corresponds to a mean power which during icing varies very little with wind speed.

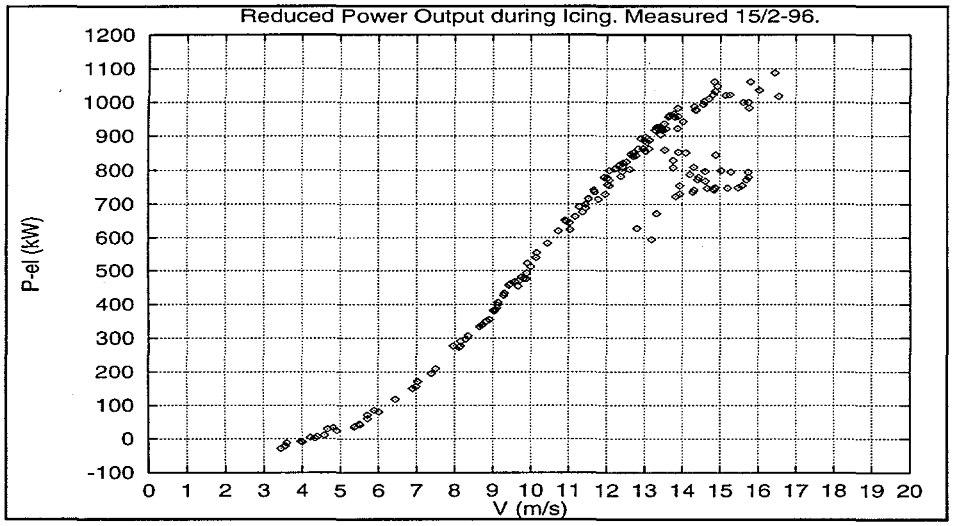

Figure 4.1-3 Measured power output from iced and un-iced rotor. 10-minute-values from 15th of February 1996.

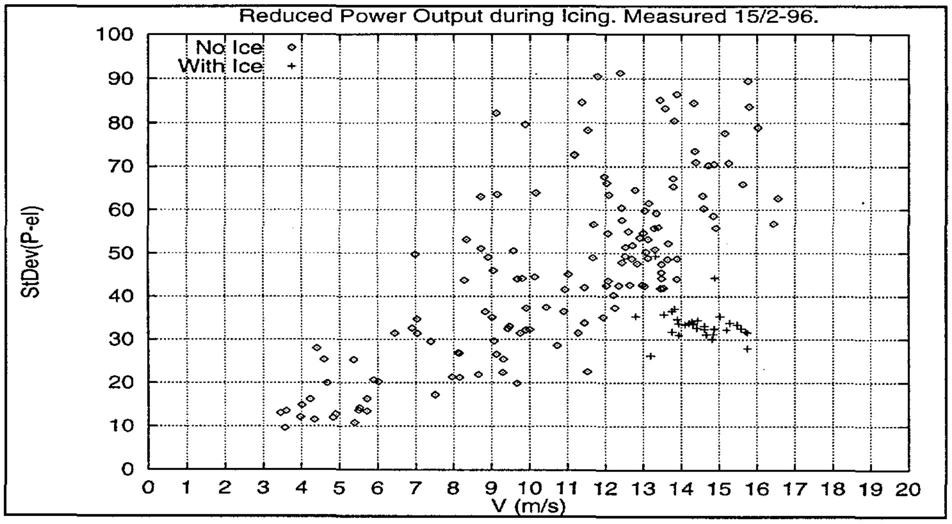

Figure 4.1-4 Standard deviation of measured power output from iced and un-iced rotor. 10-minute-values from 15th of February 1996.

4. Turbine Loads with and without ice

In this chapter examples are presented of loads measured with and without ice on the blades. It is important to stress the fact that even with exactly the same mean wind speed, standard deviation of wind speed and power spectral density of wind speed measured in one point, the wind can be significantly different and cause different load-spectra from a turbine. This means that the analysis given here is no more than one example, which gives an indication of the importance of light icing.

4.1 Operation in stalled condition

In this section two selected time-series are investigated in more detail. They have mean wind speeds of 15.3 m/s and 15.7 m/s respectively, turbulence intensity of 7% in both cases and mean yaw-errors of 7 and 6 degrees respectively. The first series was measured while the rotor was iced, the second while the rotor was ice-free. Figure 4.1-1 give statistical data for the two time-series.

WITH ICE (15/2-96 18.11):

	Mean	Min	Max	Std.Dev.
FlapRoot (V)	-3.77	-5.79	-1.46	0.61
EdgeRoot (V)	-12.13	-18.10	-5.34	3.47
Flap,r=7m (V)	-5.17	-8.38	-1.82	1.14
Flap,r=13m (V)	-4.20	-8.74	1.04	1.46
Flap,r=17m (V)	0.21	-3.61	4.13	1.07
ShaftTorsion (V)	2.21	1.87	2.61	0.096
MxShaft (V)	-1.21	-7.14	4.55	2.99
MyShaft (V)	2.84	-2.92	8.50	3.03
MxTowerBase (V)	0.74	0.37	1.16	0.097
MyTowerBase (V)	1.13	0.77	1.51	0.108
TowerTopTorsion (V)	-0.453	-0.698	-0.232	0.054
PowerGen1 (kW)	406.1	345.4	476.6	16.8
PowerGen2 (kW)	407.0	346.0	477.3	16.7
Vhub (m/s)	15.70	11.93	18.92	1.13
Wdir (deg.)	241.1	233.3	250.5	2.57
YawDir (deg.)	233.9	233.8	233.9	0.01
Temp (deg. C)	0.04	0.00	0.11	0.03

NO ICE (17/2-96 03.38):

	Mean	Min	Max	Std.Dev.
FlapRoot (V)	-4.48	-6.64	-2.32	0.57
EdgeRoot (V)	-12.67	-18.66	-6.20	3.41
Flap,r=7m (V)	-6.20	-9.65	-2.65	1.00
Flap,r=13m (V)	-5.52	-10.18	-0.60	1.24
Flap,r=17m (V)	-0.88	-4.61	2.74	0.91
ShaftTorsion (V)	2.87	2.14	3.56	0.210
MxShaft (V)	-1.01	-6.45	5.41	2.81
MyShaft (V)	2.74	-3.15	8.49	2.77
MxTowerBase (V)	0.30	-0.08	0.68	0.113
MyTowerBase (V)	1.43	1.09	1.79	0.107
TowerTopTorsion (V)	-0.479	-0.767	-0.183	0.057
PowerGen1 (kW)	521.0	392.3	635.6	36.2
PowerGen2 (kW)	518.8	391.7	633.9	36.0
Vhub (m/s)	15.25	11.75	18.58	1.09
Wdir (deg.)	264.4	253.6	275.4	3.26
YawDir (deg.)	258.3	257.1	261.4	1.79
Temp (deg. C)				

Figure 4.1-1 Statistical data for the two measured time-series analysed in this chapter.

4.1.1 Time-tracks of power and flaproot moment

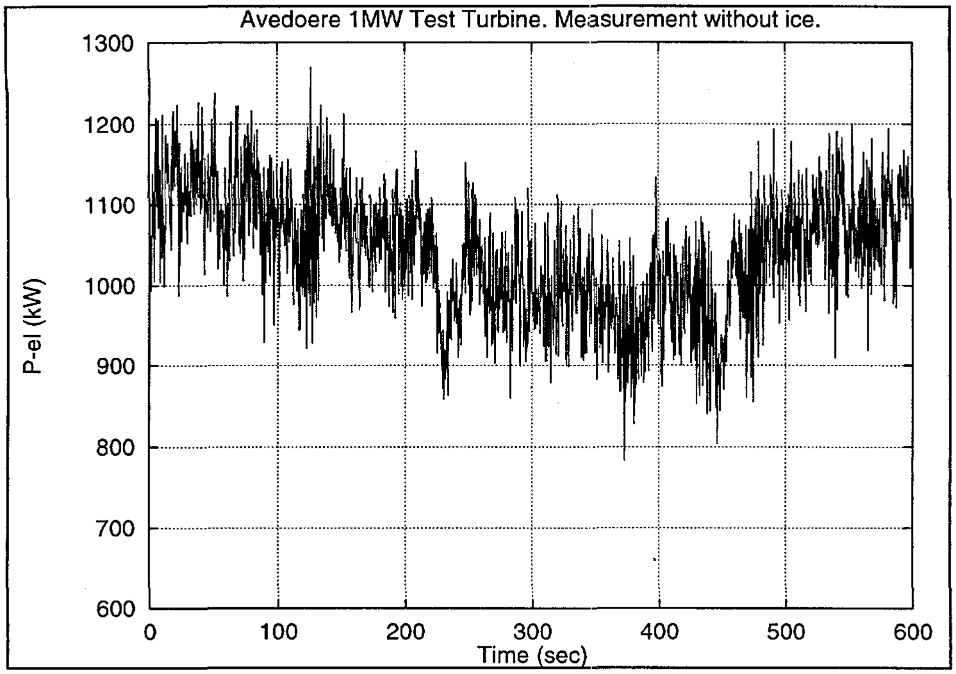

Figure 4.1-2 Time-track of electrical power without ice on rotor.

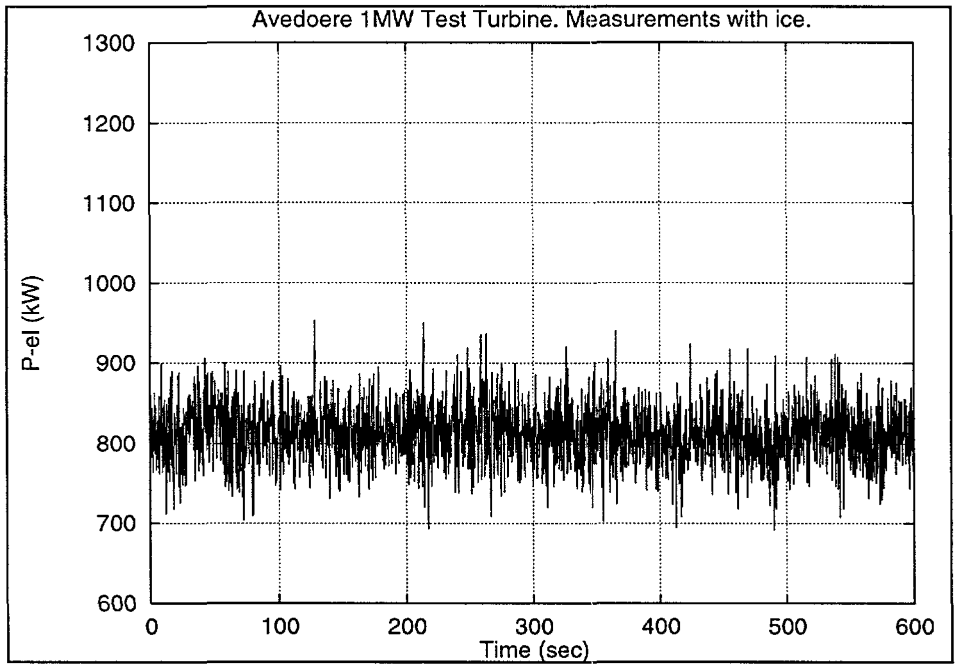

Figure 4.1-3 Time-track of electrical power with ice on rotor.

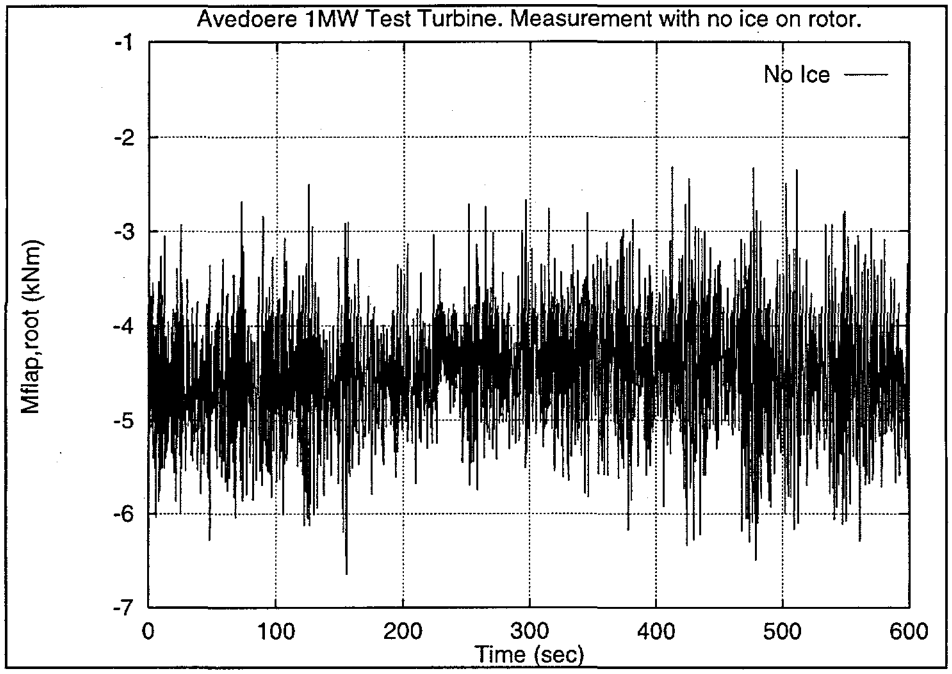

Figure 4.1-4 Time-track of flapmoment in root for ice-free rotor.

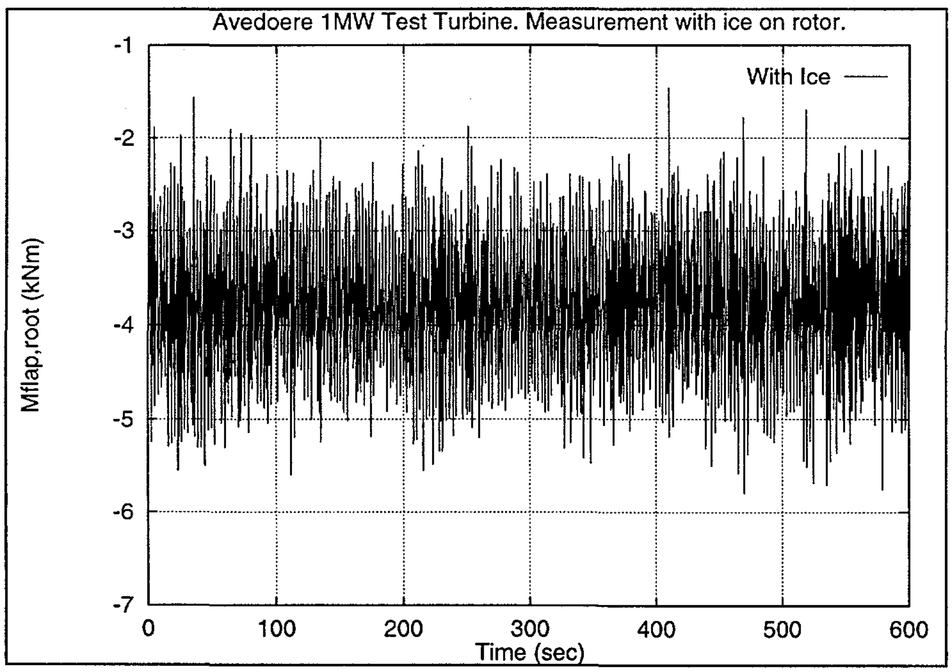

Figure 4.1-5 Time-track of flapmoment in root for iced rotor.

4.1.2 PSD's of loads

Figure 4.1-6 shows PSD's of the wind speeds for the two time-series analysed in this section. The wind speeds were measured with cup-anemometers on the meteorological mast in front of the wind turbine. One case is with ice on the rotor, the other without ice. The spectra are fairly equal, indicating comparable wind input and absence of ice on the anemometer, while the turbine-rotor was iced.

Figure 4.1-7 shows PSD's of flapmoments measured in bladeroot with ice-free rotor as well as with iced rotor. Figure 4.1-8 shows PSD's of flapmoments measured at 17 m radius from the same time-series. Icing is seen to increase the energy-content at 1P (0.39 hz), and almost double it at the flap-eigenfrequency of 1.45 Hz. The increased 1P-vibration is probably due to aerodynamic unbalance as very little difference is seen for edgemoment in Figure 4.1-9, and tower top torsion in Figure 4.1-11. The increased vibration at flapeigenfrequency is therefore probably also due to changed aerodynamics.

Figure 4.1-9 and Figure 4.1-10 show PSD's of edgemoment with and without ice in linear and logarithmic plots respectively. At 1P icing slightly increases the energy-content, and at edge-eigenfrequency the energy-content is doubled.

Figure 4.1-11 and Figure 4.1-12 show PSD's of tower top torsion with and without ice in linear and logarithmic plots respectively. 1.19 Hz is the yaw-eigenfrequency at stand still, which during operation should be felt at frequencies 1P higher and lower than this, i.e. at 0.8hz and 1.58hz, as can actually be seen in the measured PSD's (these two vibrations can be felt by the flaproot at around 1.2 hz as seen in Figure 4.1-8).

Figure 4.1-13 and Figure 4.1-14 show PSD's of shaft torque with and without ice in linear and logarithmic plots respectively. During icing 3P-vibration is strongly reduced, whereas the energy-content at the tower-eigenfrequency of 0.65 Hz is moderately increased.

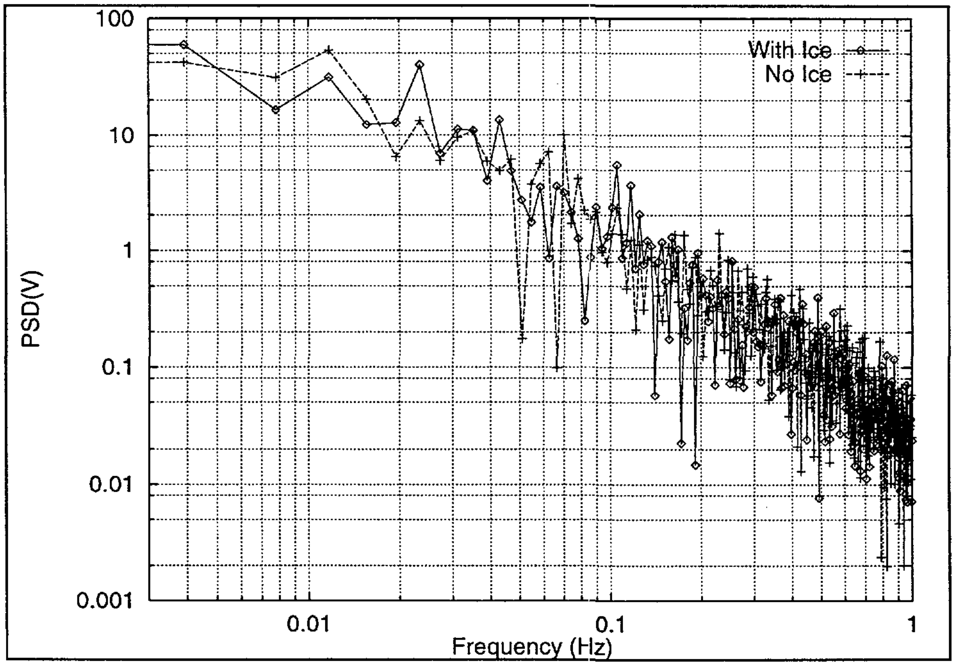

Figure 4.1-6 PSD's of wind speed measured with cup anemometer on meteorology mast with and without ice on the rotor. In both cases V=15m/s and I=7%.

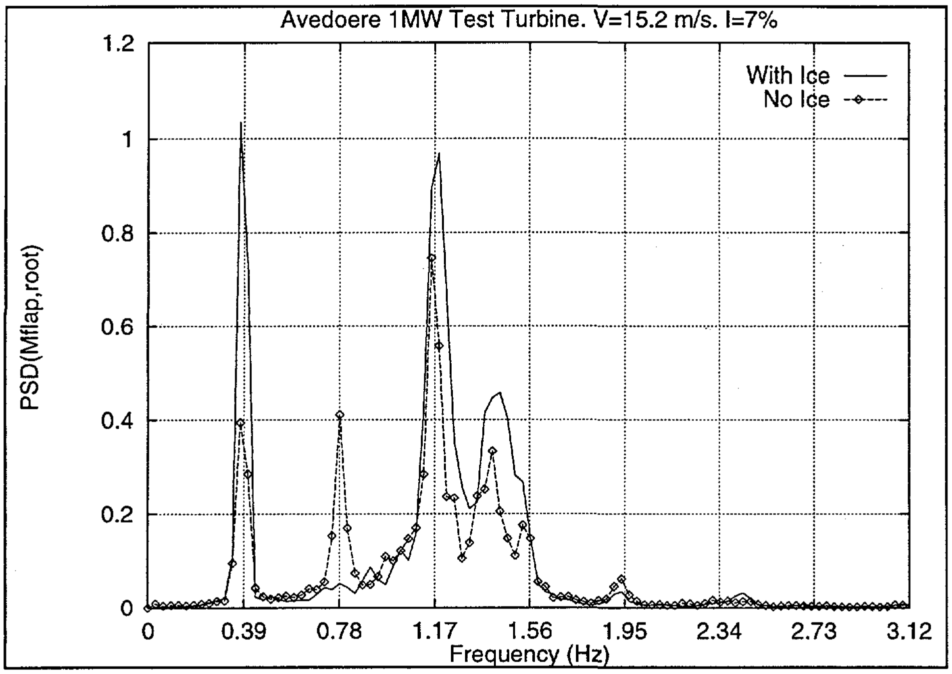

Figure 4.1-7 PSD's of flapmoment measured in bladeroot on rotor with and without ice. In both cases V=15m/s and I=7%.

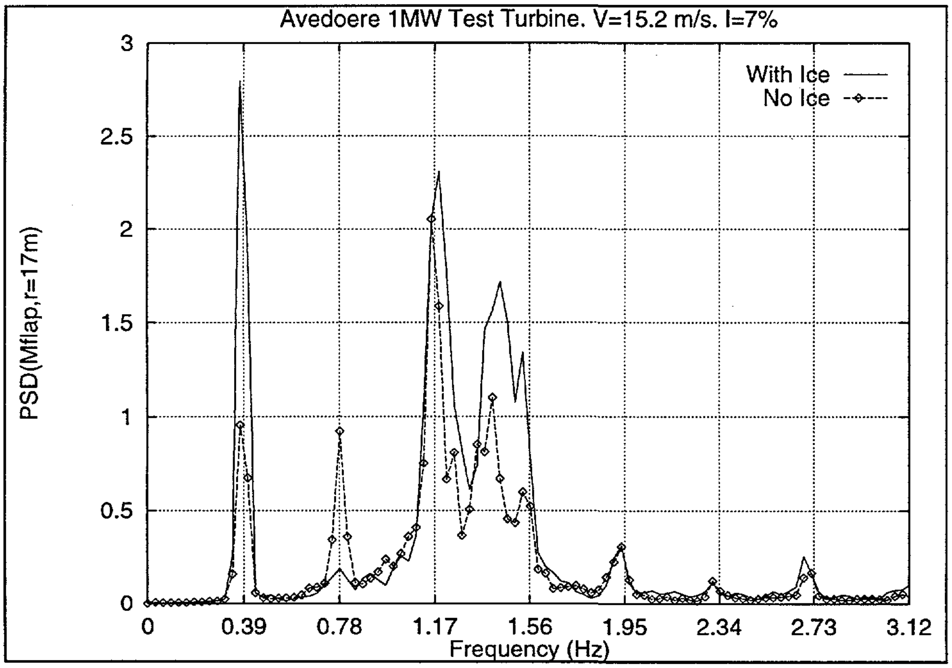

Figure 4.1-8 PSD's of flapmoment measured at radius 17m on rotor with and without ice. In both cases V=15m/s and I=7%.

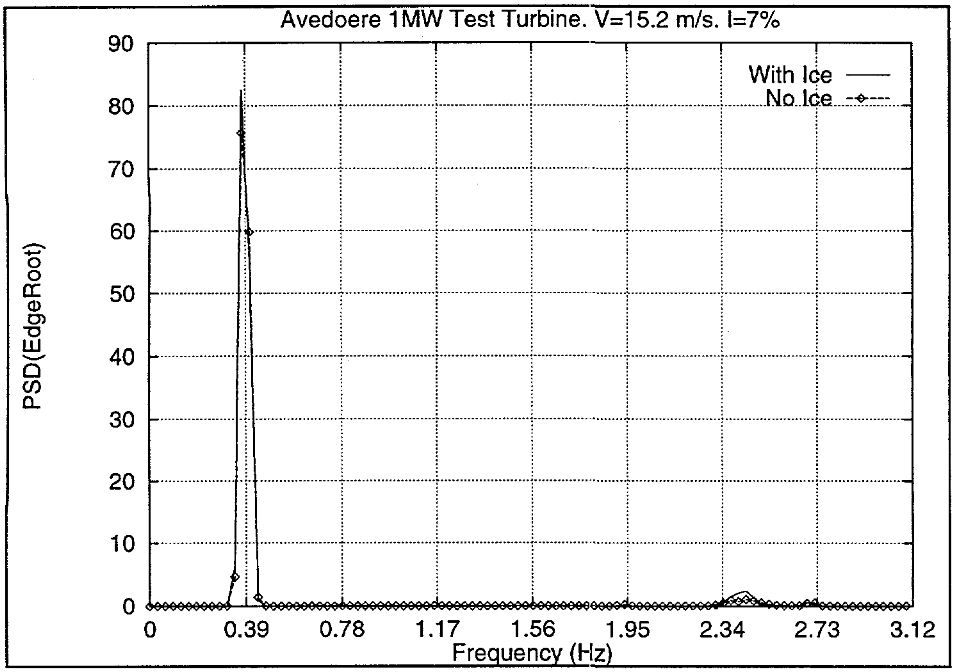

Figure 4.1-9 PSD's of edgemoment measured at bladeroot on iced and un-iced rotor. In both cases V=15m/s and I=7%.

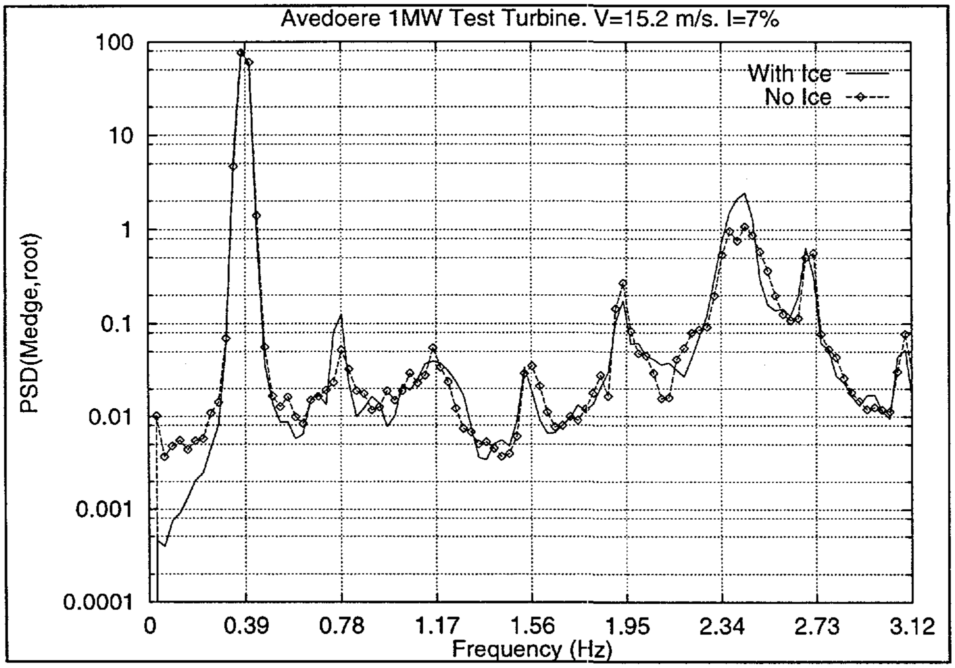

Figure 4.1-10 PSD's of edgemoment measured at bladeroot on rotor with and witout ice. In both cases V=15m/s and I=7%.

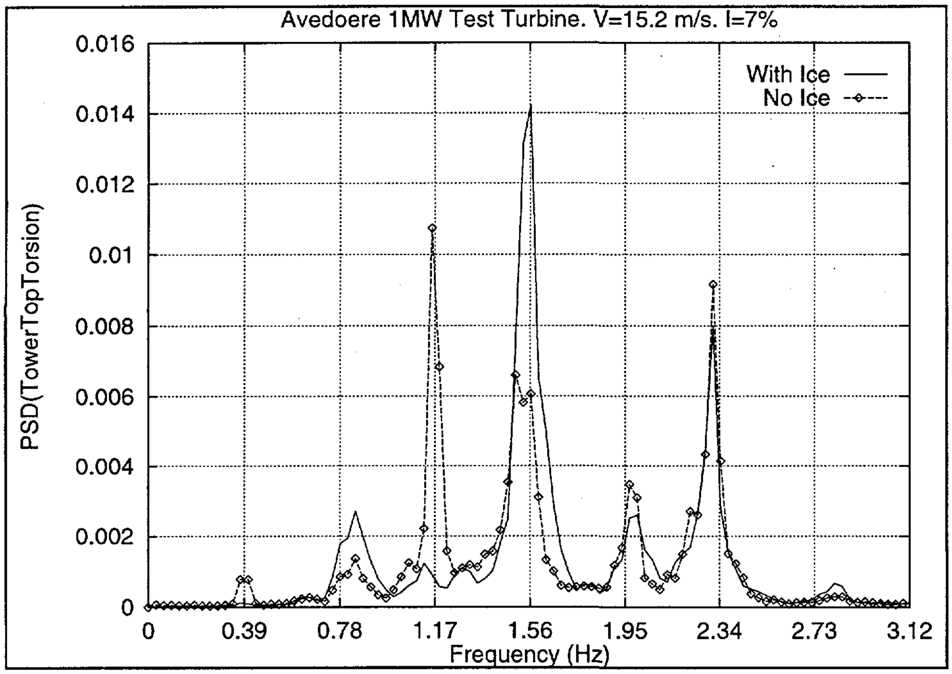

Figure 4.1-11 PSD's of measured tower top torsion on rotor with and witout ice. In both cases V=15m/s and I=7%.

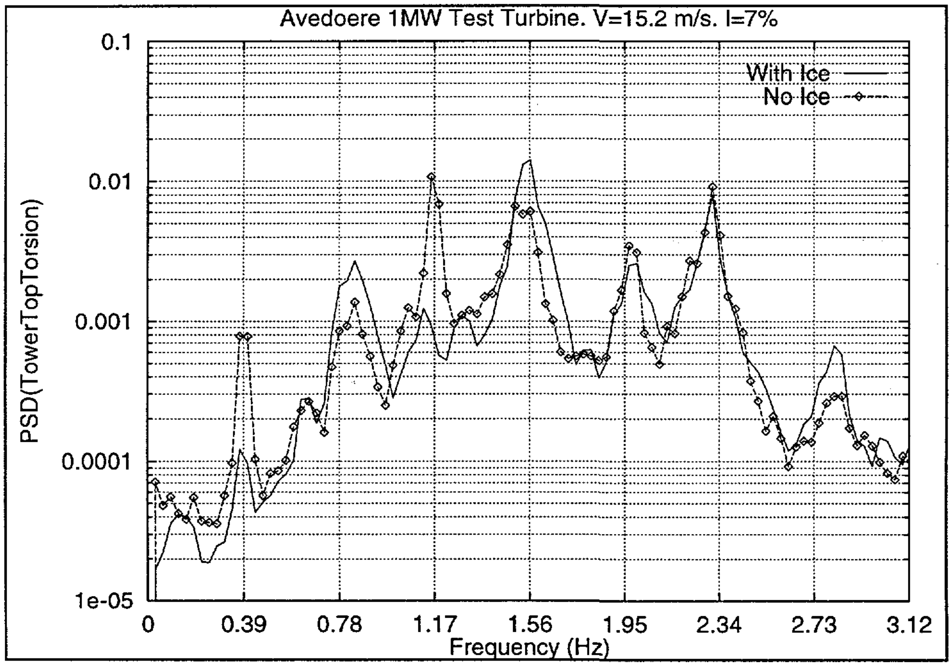

Figure 4.1-12 PSD's of measured tower top torsion on rotor with and without ice. In both cases V=15m/s and I=7%.

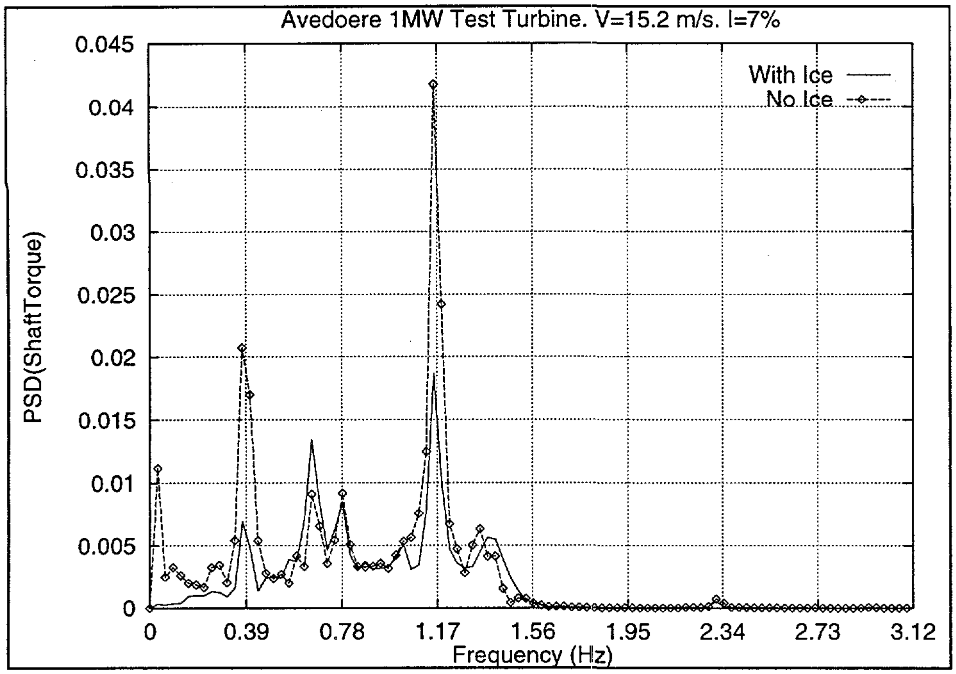

Figure 4.1-13 PSD's of measured shaft torque with iced and un-iced rotor. In both cases V=15m/s and I=7%.

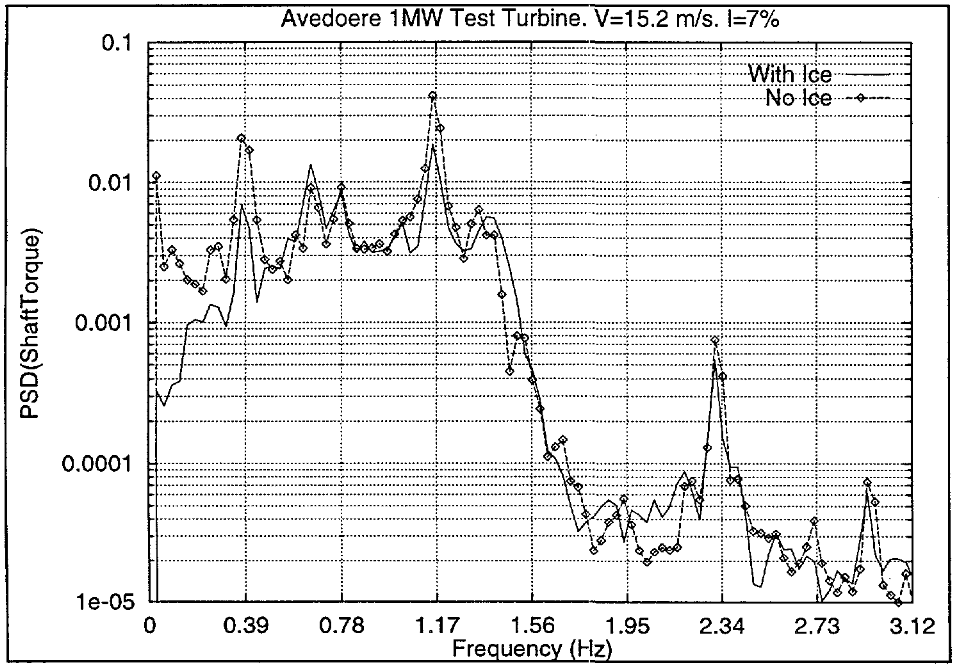

Figure 4.1-14 PSD's of measured shaft torque with iced and un-iced rotor. In both cases V=15m/s and I=7%.

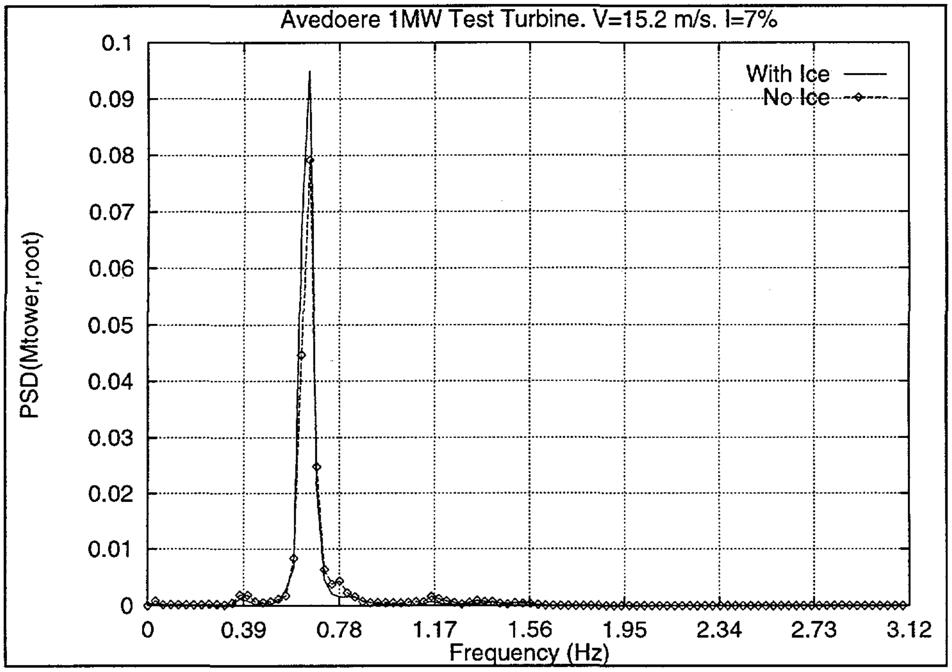

Figure 4.1-15 PSD's of tower-root bending with rotor iced and un-iced.

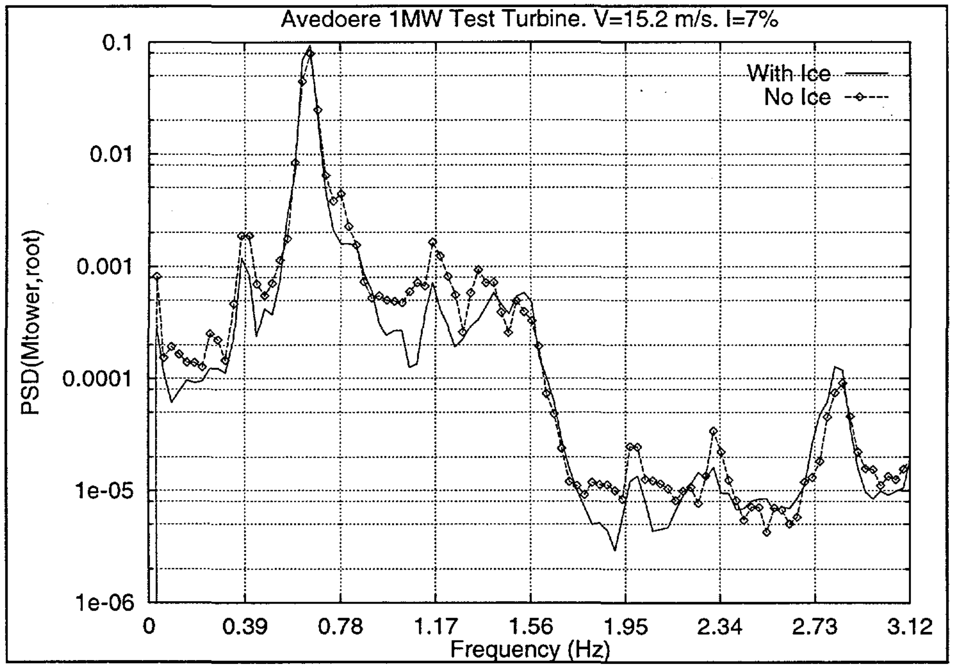

Figure 4.1-16 PSD's of tower-root bending with rotor iced and un-iced.

4.1.3 Azimuth-binned loads

In this chapter azimuth-binned flap- and edge-moments as well as shaft torque are shown. In the evaluation of these it is important to keep in mind that this, the deterministic, part of the signal is much smaller than the stochastic.

Figure 4.1-17 show azimuth-binned flapmoment in blade root. With ice the amplitude is larger. With ice the effect of the tower shadow is much reduced.

Figure 4.1-18 show azimuth-binned flapmoment at 17m radius, i.e. at 50% radius. With ice the amplitude is unchanged. With ice the effect of the tower shadow is reduced.

Figure 4.1-19 show azimuth-binned edgemoment in blade root. Very little difference between ice and no ice is seen.

Figure 4.1-20 show azimuth-binned shaft torque without ice, with ice and during the proces of de-icing. Mean levels are different corresponding to mean of power. 3P variations are slightly dampend at icing.

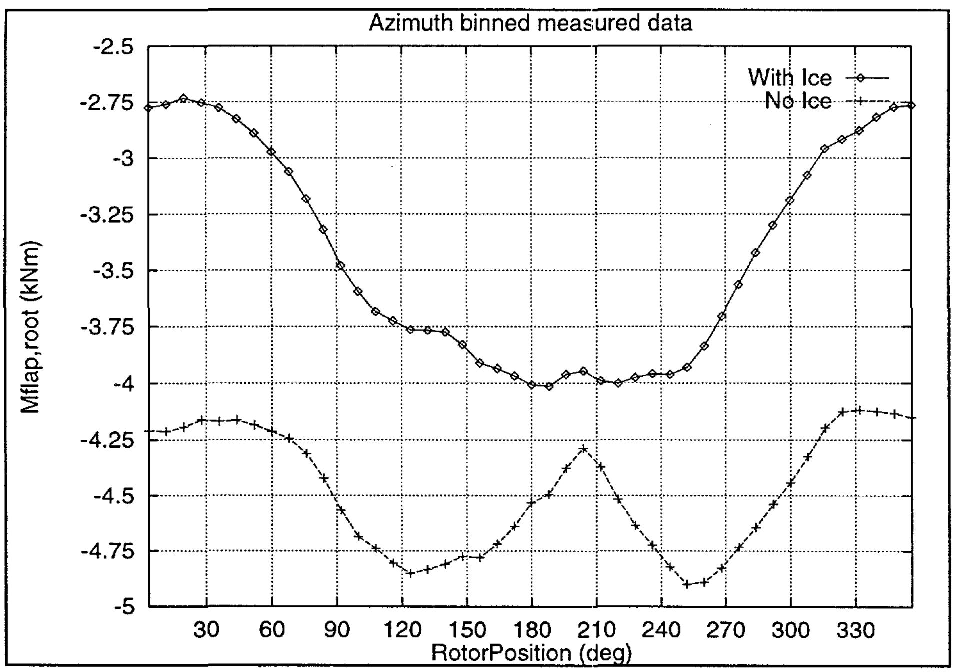

Figure 4.1-17 Azimuth-binned flapwise blade root moments with and without ice on the blade.

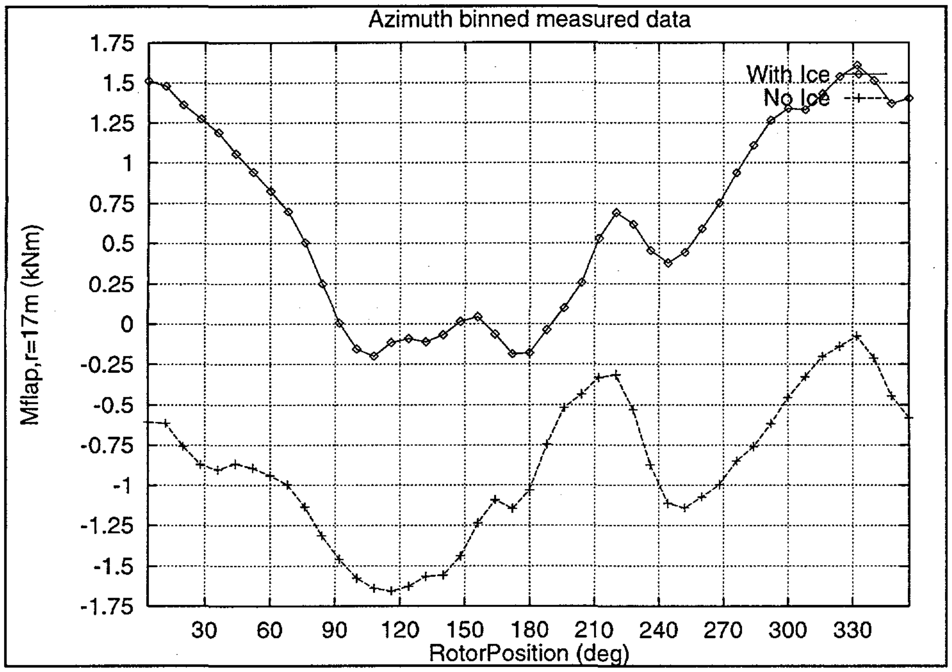

Figure 4.1-18 Azimuth-binned flap moments at r=17m with and without ice on the blade.

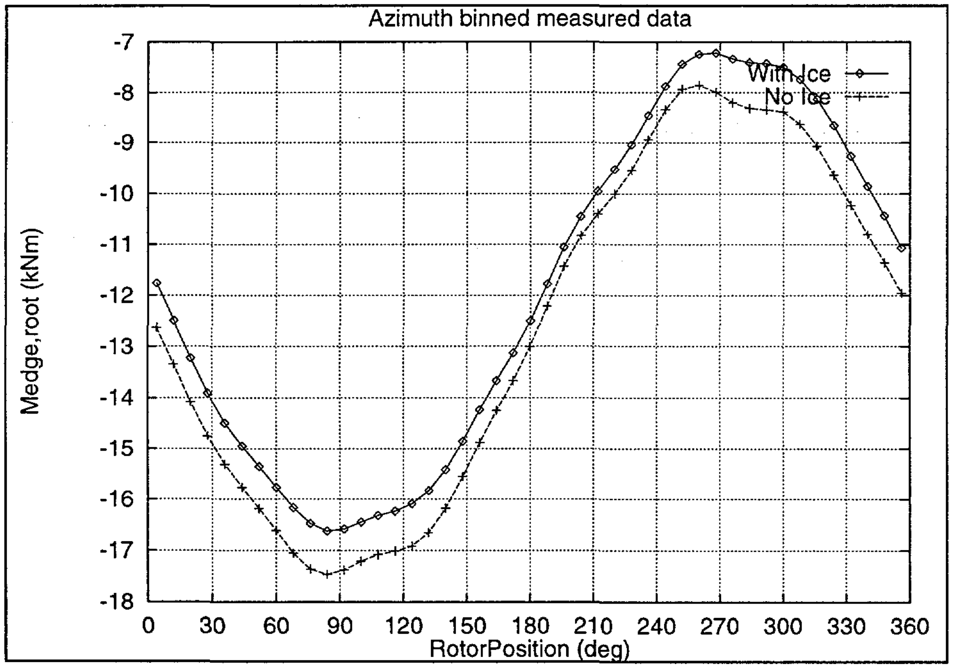

Figure 4.1-19 Azimuth-binned edge moment at root with and without ice on the blade.

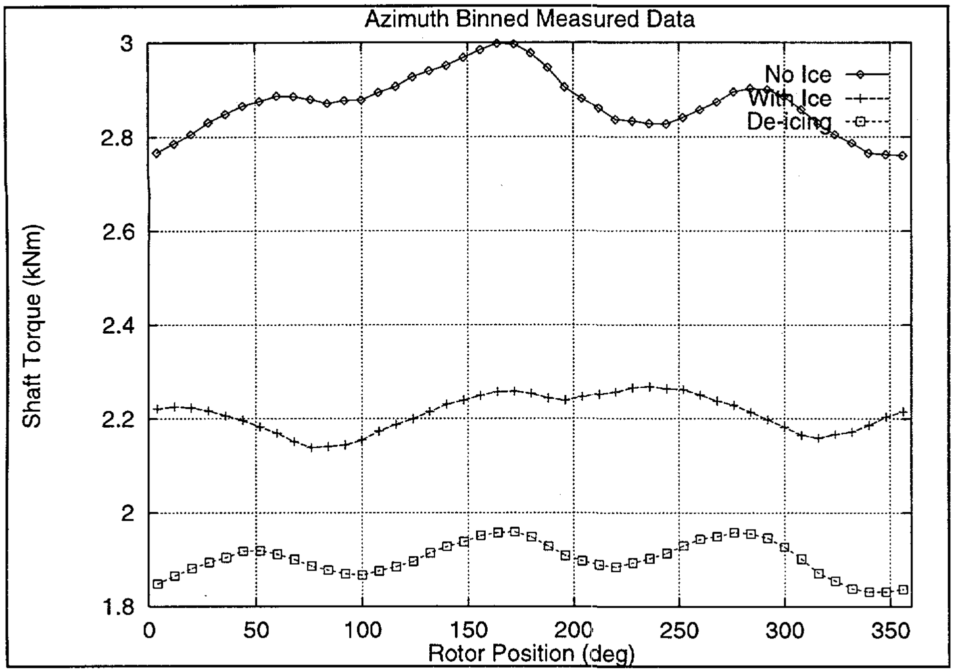

Figure 4.1-20 Azimuth-binned Shaft Torque without ice, with ice and during de-icing.

4.1.4 Measurements during de-icing of rotor

The period of icing of the rotor ends after 5 hours. The time-series reported in this chapter was measured 20 minutes before icing ended. Figure 4.1-21 shows power, and in the period the level is seen to rise from around 650 kW to around 770 kW. Figure 4.1-22 shows simultaneously measured wind speed, and the level is seen to rise from around 13 m/s to around 13.5 m/s. The power curve, Figure 4.1-3, suggests that the wind speed difference corresponds to a power difference of only 60 kW. The rest of the difference is due to de-icing of the rotor.

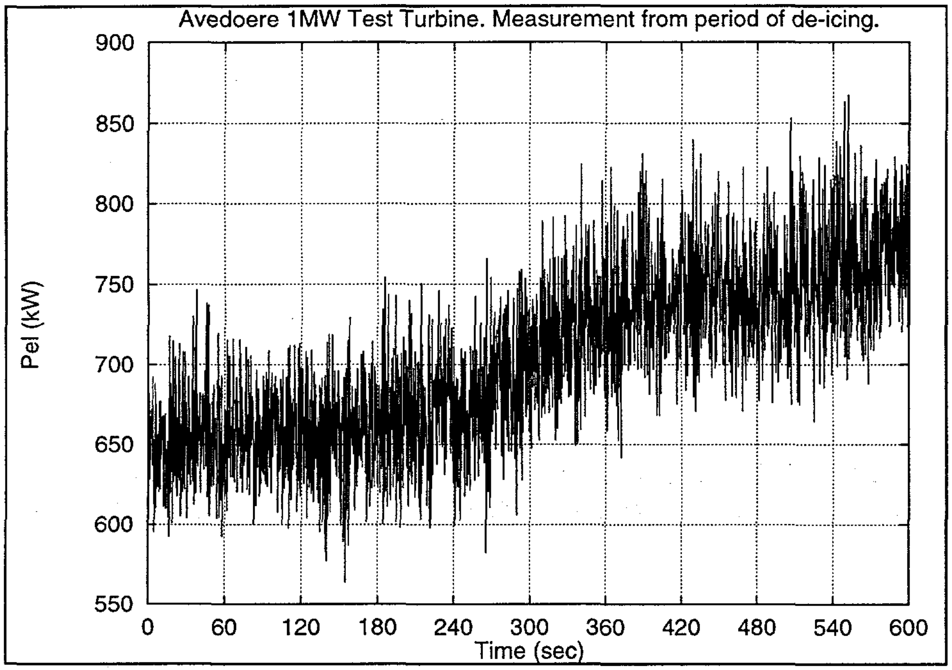

Figure 4.1-21 Time-track of electrical power during de-icing of rotor.

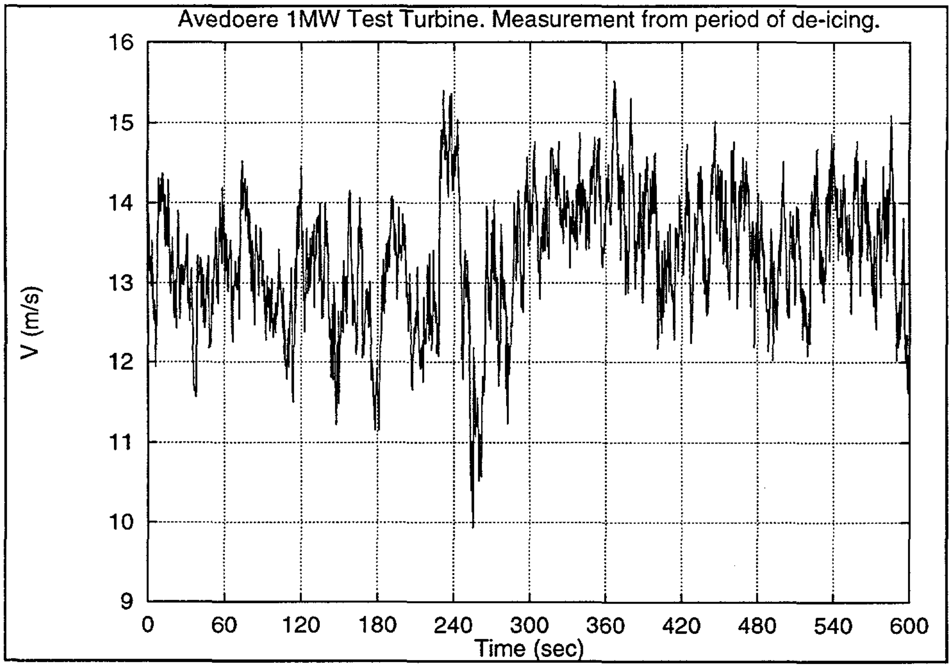

Figure 4.1-22 Wind speed during de-icing of rotor.

4.2 Operation at 10 m/s

In this section two selected time-series are investigated in more detail. They have mean wind speeds of 10.1 m/s and 10.5 m/s respectively and turbulence intensities of 7% and 5%. Mean yaw-errors are 6 and 9 degrees respectively. The first was measured while the rotor was iced, the second while the rotor was ice-free. Figure 4.1-1 give statistical data for the two data-files.

WITH ICE (12/1-97 19.46):

	Mean	Min	Max	Std.Dev.
FlapRoot (V)	-2.98	-4.07	-1.88	0.324
EdgeRoot (V)	-6.10	-11.5	-0.694	3.36
Flap,r=17m (V)	0.984	-0.567	2.96	0.420
ShaftTorsion (V)	1.33	0.92	1.76	0.14
MxShaft (V)	-1.29	-5.68	3.19	2.64
MyShaft (V)	2.75	-2.05	7.05	2.64
MxTowerBase (V)	0.866	0.709	0.987	0.0399
MyTowerBase (V)	0.593	0.460	0.728	0.0471
TowerTopTorsion(V)	-0.412	-0.588	-0.283	0.0243
PowerG1+G2 (kW)	503.06	360.71	649.18	50.34
Vhub (m/s)	10.08	8.29	11.88	0.67
Wdir (deg)	217.8	208.6	227.2	2.94
YawDir	211.6	208.9	212.6	1.66
Temp	-1.52	-1.57	-1.46	0.026

NO ICE (13/1-97 01.46):

	Mean	Min	Max	Std.Dev.
FlapRoot (V)	-3.56	-4.90	-0.009	0.349
EdgeRoot (V)	-6.16	-11.4	-0.597	3.32
Flap,r=17m (V)	0.112	-1.69	1.88	0.441
ShaftTorsion (V)	1.61	1.32	1.92	0.08
MxShaft (V)	-1.30	-5.60	3.06	2.45
MyShaft (V)	2.74	-1.41	6.71	2.44
MxTowerBase (V)	0.674	0.548	0.789	0.0350
MyTowerBase (V)	0.965	0.836	1.08	0.0365
TowerTopTorsion (V)	-0.462	-0.581	-0.354	0.0329
PowerG1+G2 (kW)	602.31	492.64	708.40	29.40
Vhub (m/s)	10.53	8.31	12.81	0.54
Wdir (deg)	243.3	235.4	253.4	2.36
YawDir	234.2	233.4	235.8	1.11
Temp	0.42	0.33	0.52	0.041

Figure 4.2-1 Statistical data for the two measured time-series analysed in this section.

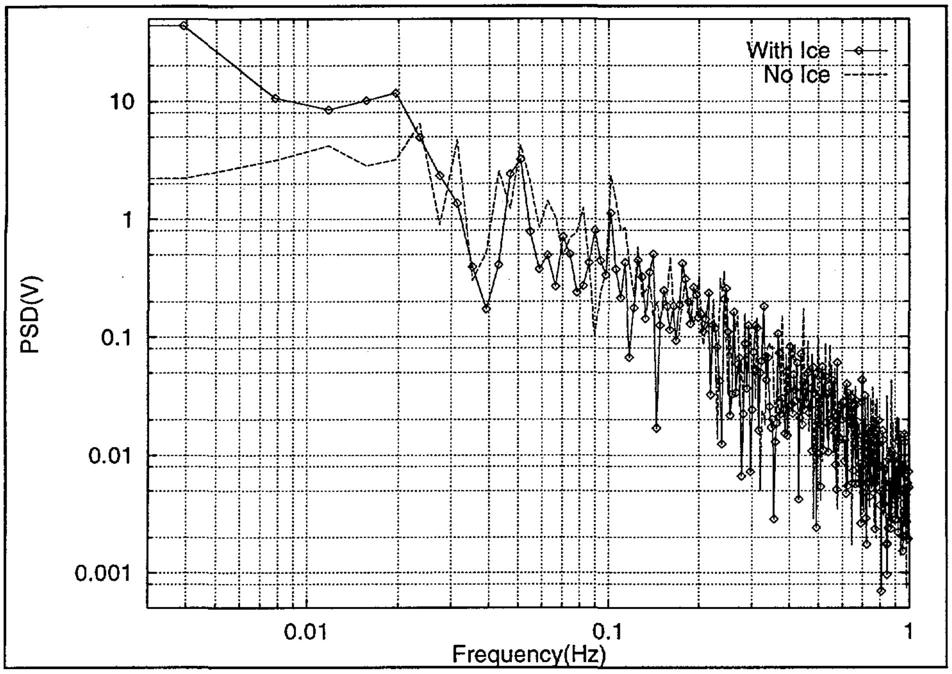

Figure 4.2-2 PSD's of wind speed measured with cup anemometer on met.mast with and without ice on the rotor. With ice V=10.1m/s and I=7%, without ice V=10.5m/s and I=5%.

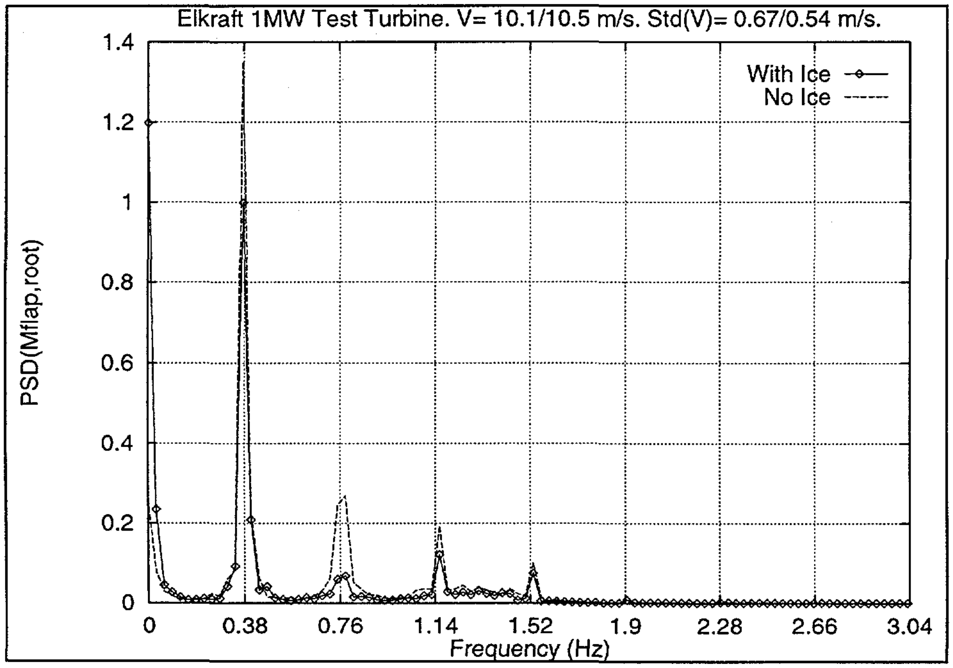

Figure 4.2-3 PSD's of flapmoment measured in bladeroot on rotor with and without ice. V=10m/s, I~6%.

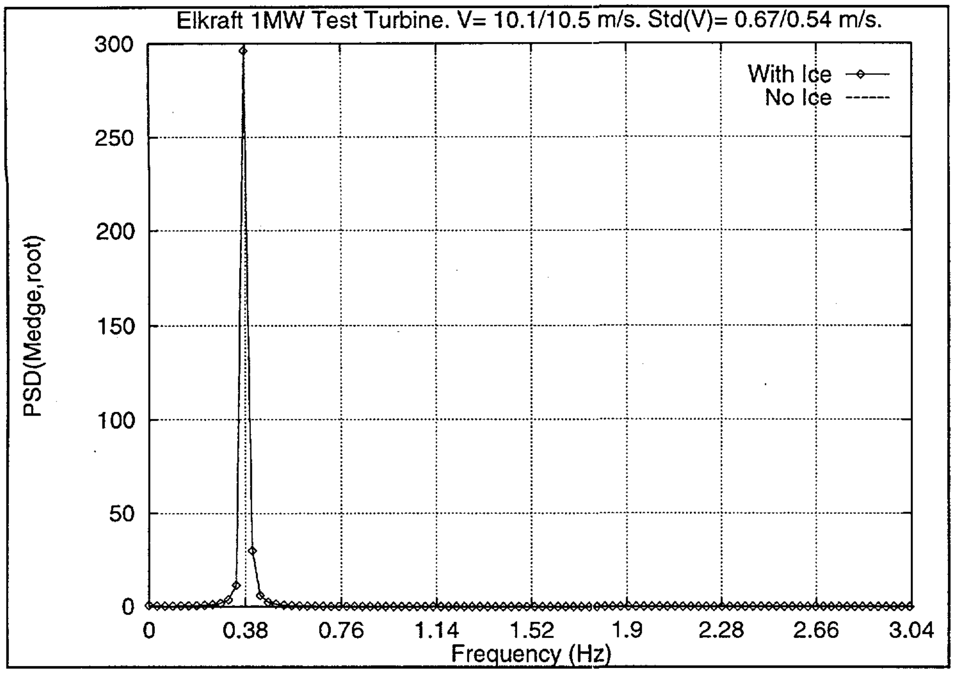

Figure 4.2-4 PSD's of edgemoment measured in bladeroot on rotor with and without ice. V=10m/s, I~6%. Logarithmic plot in Figure 4.2-5.

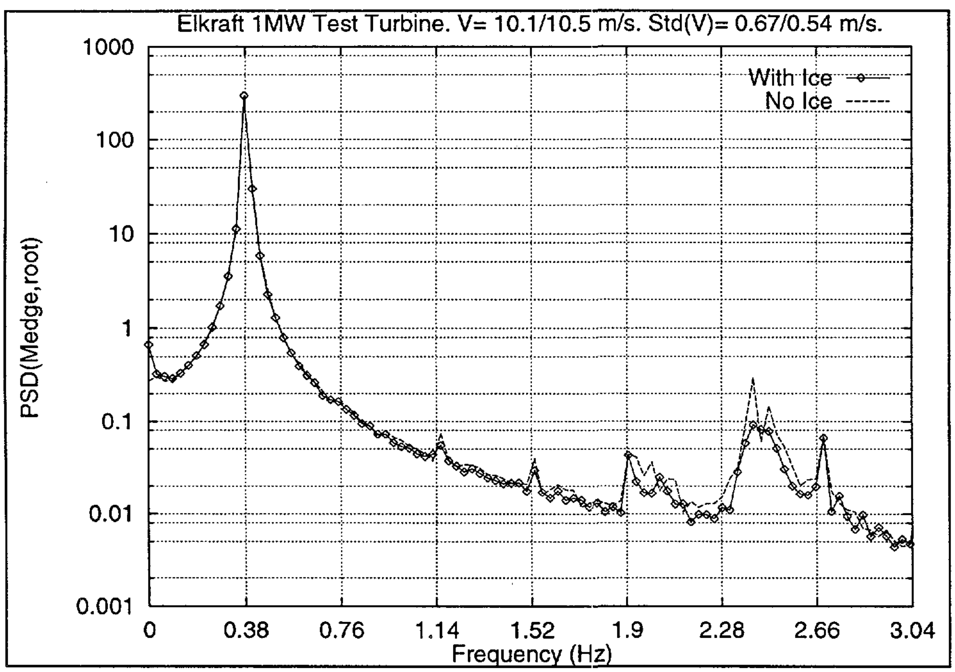

Figure 4.2-5 PSD's of edgemoment measured in bladeroot on rotor with and without ice. V=10m/s, I~6%.

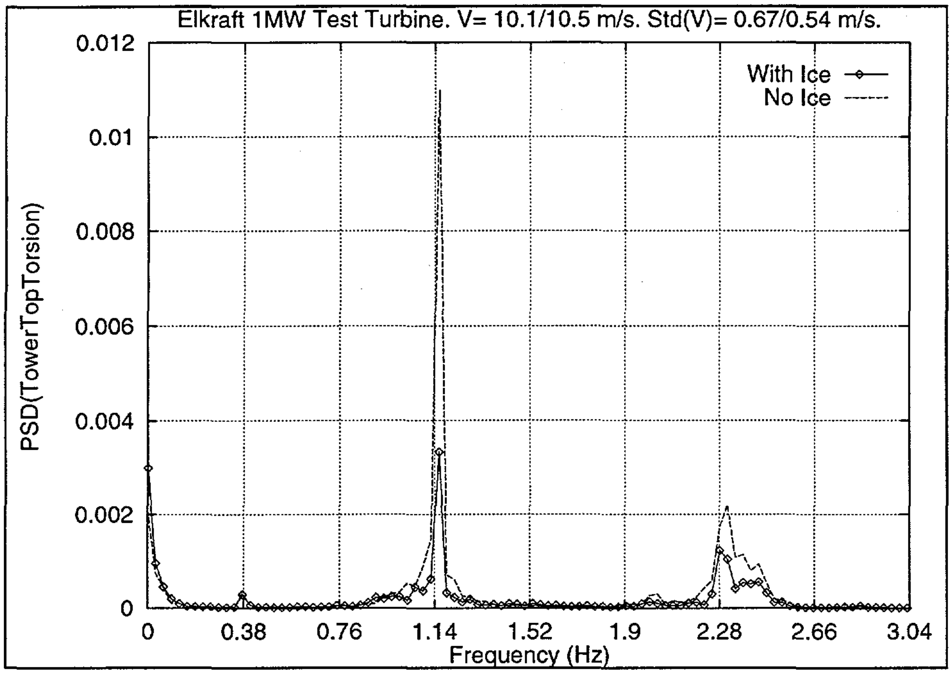

Figure 4.2-6 PSD's of measured tower top torsion with and without ice. V=10m/s, I~6%. Logarithmic plot in Figure 4.2-7.

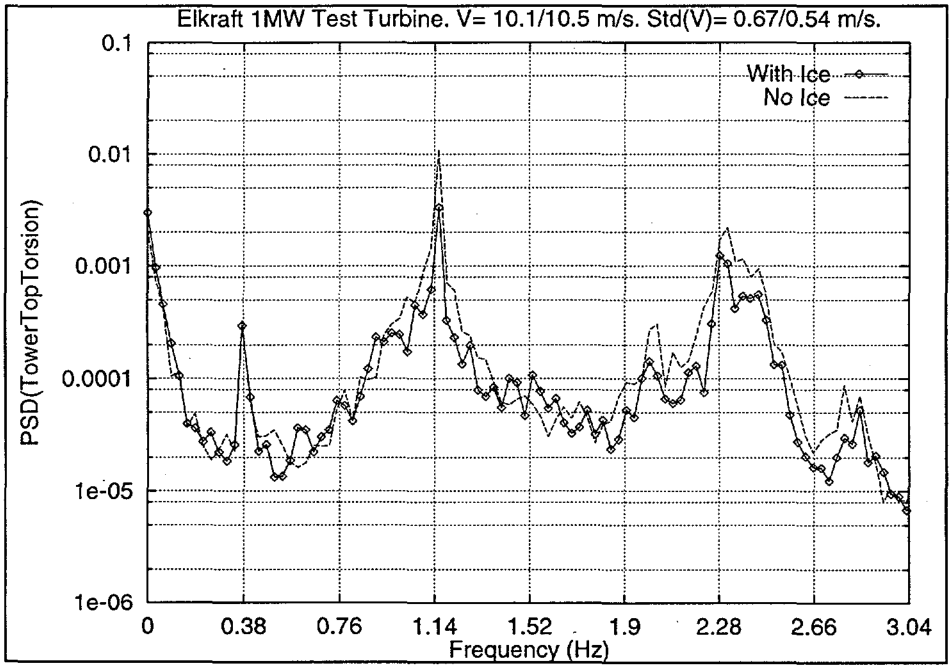

Figure 4.2-7 PSD's of measured tower top torsion with and without ice. V=10m/s, I~6%.

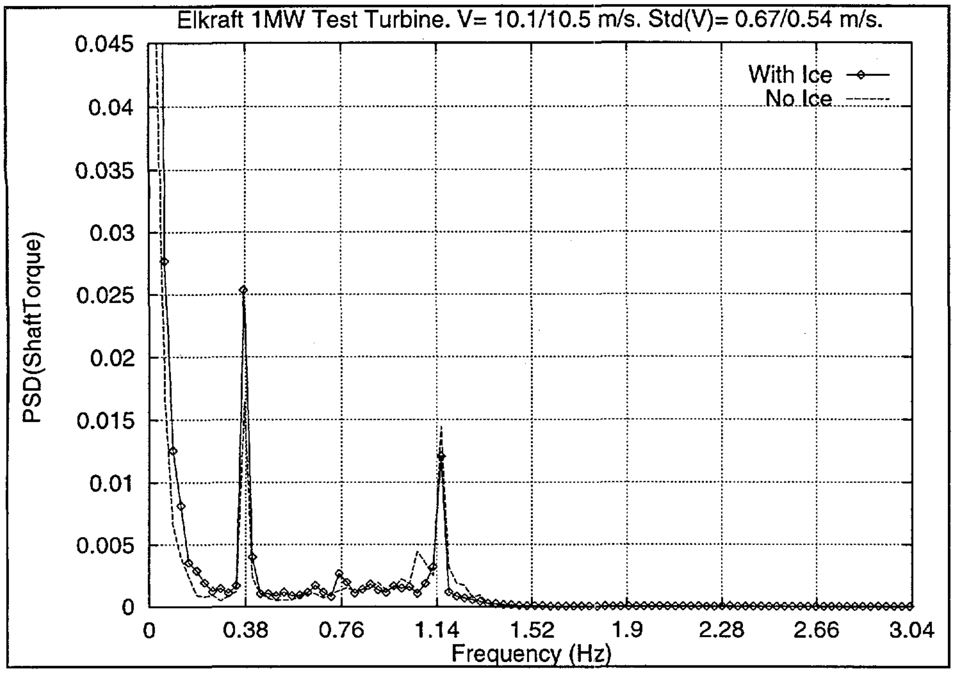

Figure 4.2-8 PSD's of measured shaft torque with and without ice. V=10m/s, I~6%. Logarithmic plot in Figure 4.2-9.

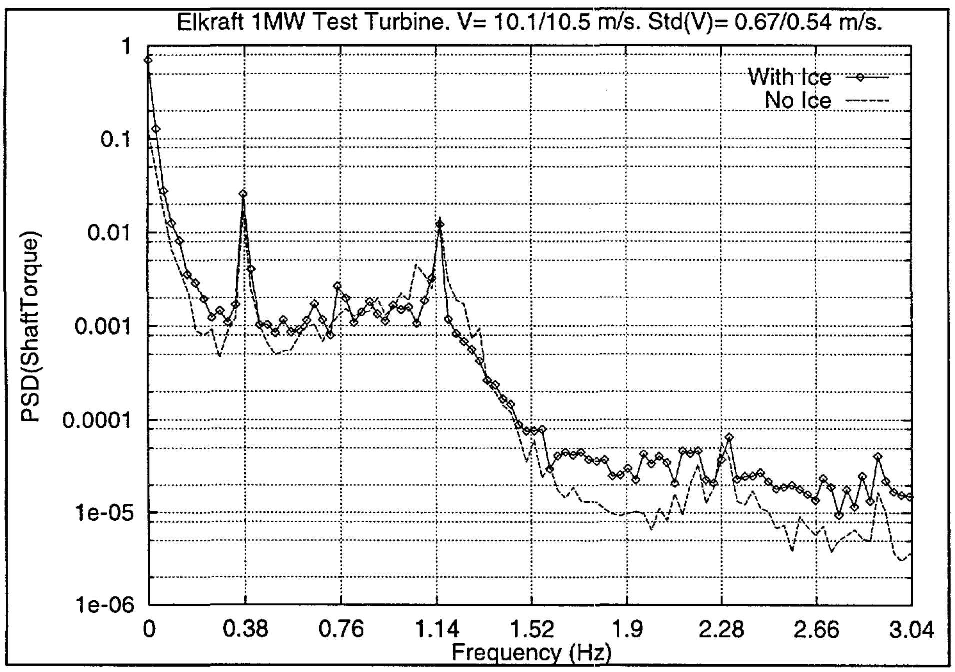

Figure 4.2-9 PSD's of measured shaft torque with and without ice. V=10m/s, I~6%.

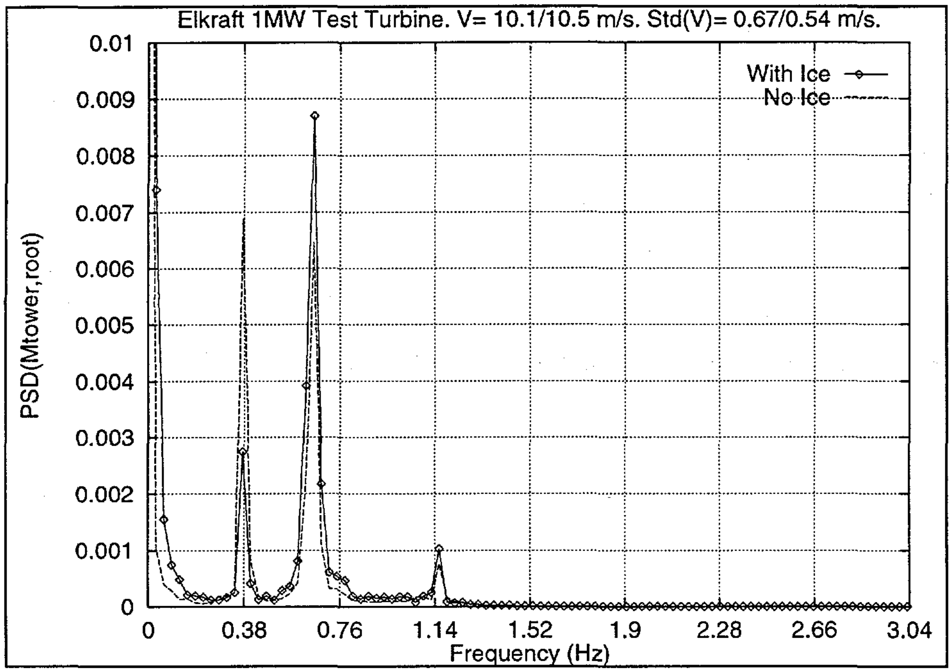

Figure 4.2-10 PSD's of measured tower root bending with and without ice. V=10m/s, I~6%. Logarithmic plot in Figure 4.2-11.

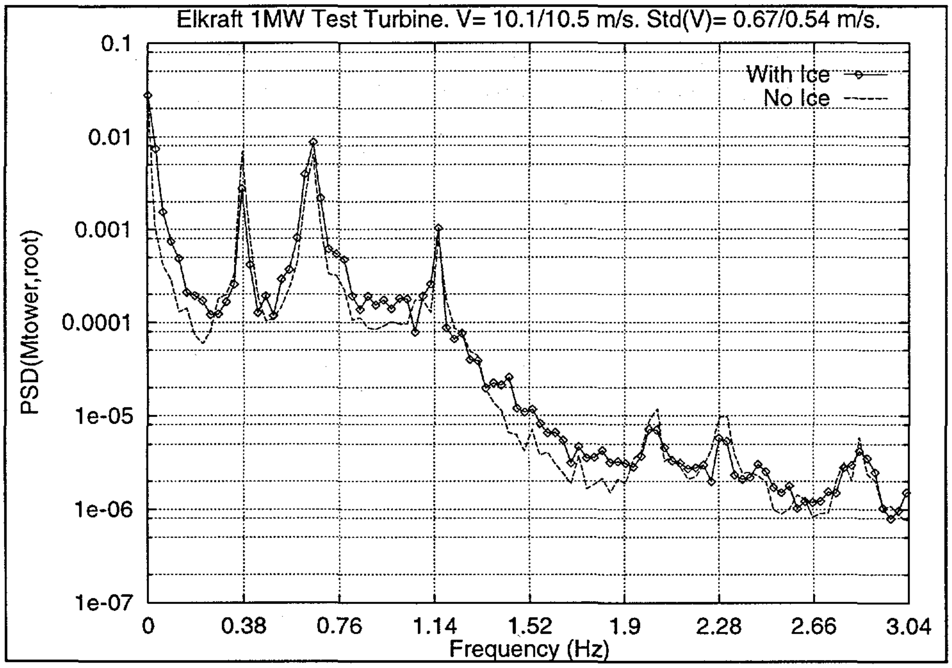

Figure 4.2-11 PSD's of measured tower root bending with and without ice. V=10m/s, I~6%.

5. Conclusion

The analysed data show a 25% decrease of mean power during operation at 15 m/s over a 5 hour period. The analysed time-series from icing at 10 m/s show a 20% decrease of mean power.

Standard deviation of power was reduced to less than half during icing at 15 m/s. At 10 m/s standard deviation of power was reduced by almost half during icing.

Standard deviations of all loads, except the power and shaft torque, are found to be no more than marginally changed by icing.

The flap- and edge-moments have increased energy content at the respective eigenfrequencies.

De-icing occurs rather smoothly and without any sudden impulses in load-signals.

6. Discussion

Limitations to the presented results are numerous, and should not all be mentioned here, but important to notice is: only one stall-controlled turbine is concerned, only measurements at 10 m/s and 15 m/s have been investigated, the amount of ice is believed to have been 1-3 cm on the leading edge - but this was neither measured nor photographed or observed.

At more severe cases of icing the reduction in mean power output can probably be much larger than the reduction of 20-25% reported here, and probably the turbine will start at higher wind speeds when blades are iced. It is obvious that the energy loss from a turbine operating in areas with frequent cases of icing can be significant. The reduction observed at 10 m/s proposes that pitch controlled turbines will see power reduction of the same order. Ref.1 reports for iced profiles reduced Cl-values and increased Cd-values from measurements in wind tunnel - which corresponds well with reduced power output as reported here.

The fact that power fluctuations are reduced to half during icing, fits well with the smoothened quasi-steady Cl-curves and increased Cd-values reported for iced profiles in Ref.1.

The fact that energy-levels of flapmoment and edgemoment at the eigenfrequencies are observed to be increased by a factor of two, may not at first impression fit with the Cl- and Cd-curves reported for iced profiles in Ref. 1. But the aerodynamic damping is controlled by the shape of the hysteresis loops of the aerodynamic forces at blade vibrations, which is not investigated in Ref.1. So there is no contradiction. And the increased energy levels at the eigenfrequencies might indicate reduced aerodynamic damping, which is an important factor for the risk of occurrence of stall induced vibrations.

All loads except the power and shaft torque are reported only to be changed very little during icing, but this is probably neither true at more severe icing nor at asymmetric icing of the rotor.

7. References

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Abstract (max. 2000 characters)

When supercooled water droplets hit a rotating wind turbine blade, ice builds up at the leading edge. This heavily influences the aerodynamics of the blade - especially in stall. In severe cases the mass of ice can become a problem, but this is not typical for the few yearly cases of icing in Denmark, as the measured one presented here.

Loads were measured on the 1MW Elkraft test turbine in Denmark at two incidents of icing, namely at 10 m/s and 15 m/s. The loads are compared with measurements from ice-free conditions. The turbine is stall controlled and has a three bladed upwind rotor. It is equipped with standard LM 24 m blades and has a rotor diameter of 50 meters and a rated power of 1MW.

The two most important conclusions of the investigation are that icing reduced mean power by 25%, and that only marginal ice-induced increases of loads were found. Standard deviation of power was actually reduced to half its value, whereas the equivalent ranges of all other reported loads were marginally changed during icing. Activity of the flapwise as well as the edgewise blade bending moment was increased by a factor of two at the blade eigenfrequencies. 1P-activity of the flapwise blade bending moment was increased by a factor of three - probably due to aerodynamic unbalance.

Descriptors INIS/EDB

DENMARK; DYNAMIC LOADS; EXPERIMENTAL DATA; FREEZING; ICE; LOAD ANALYSIS; POWER GENERATION; WIND TURBINES;

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